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Optimization of Rainwater-Harvesting Dam Placement in Iraq's Western Desert: A GIS and Mathematical Modeling Approach

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Abstract: This study introduces a novel methodology for optimizing the design of small dams in the Western Desert of Iraq, a region characterized by its vast expanse and significant flood water influx, particularly in the Horan Valley. The approach integrates Geographic Information Systems (GIS) with a custom-developed Visual Basic program, termed the Optimal Height and Location Model (OHALM), to determine the most effective dam height and location. The initial phase of the study involved utilizing GIS to identify potential dam sites in Horan Valley, based on a set of defined criteria. Subsequently, OHALM was employed to ascertain the optimal dam height, taking into account economic factors such as minimal evaporation losses and maximal water storage capacity. The study culminated in the selection of 13 proposed small dam sites, with height estimations ranging between 12.5 to 14 meters, allowing for a total water storage capacity of approximately 303 million cubic meters. This capacity expansion resulted in an increase of the valley's water body area from 15 square kilometers to 90 square kilometers. Comparative analysis of these proposed dam heights with those of existing structures in the valley revealed a relative variance of 10.4% in the upstream, 7.2% in the midstream, and a comparable percentage in the downstream areas. The research highlights the efficacy of integrating GIS and Visual Basic programming for the strategic development of water resource management systems, particularly in arid regions. This innovative approach demonstrates the potential for significant improvements in water storage and management, addressing the critical need for sustainable water resources in arid environments.

Keywords: Geographic Information Systems (GIS); Optimal Height and Location Model (OHALM); Hydrological modeling; Rainwater harvesting; Water resource optimization; Dam design and placement

1 Introduction

The availability of water resources is the most important criterion that affects sustainable development. The process of planning and managing water resources is very important, especially in arid regions that suffer from varying rainfall quantities [1, 2]. According to the United Nations Environment Program (UNEP), in the year 2050, more than two billion people will suffer from water scarcity [3]. During the 20th century, a large number of dams were built, and it is estimated that the dams affect more than 60% of the rivers. About 19% of the electricity production in the world depends on hydroelectric power, and about 40% of irrigated lands around the world depend on the dams [4]. Small dams are a suitable tool for managing, storing, and distributing water because building them requires less time, cost, and effort [5].

Arid and semi-arid regions constitute about 35% of the earth's surface and cover an area of 50 million km2 of the world [6, 7]. The Iraqi Western Desert, an arid region, covers about 32% of Iraq's area [8]. The planning and management of water resources in this region is important for providing water and support the sustainable development in Iraq. Rainwater harvesting and storing water by dams reservoirs is suitable tool to conserve water in the dry season [1, 9].

The process of selecting dams' sites in these areas faces many difficulties because the dry areas are uninhabited and suffer from a severe shortage of infrastructure. GIS is a modern tool for planning in many fields as a water resources management [10]. GIS provides a simplification of the optimum dams' site selection process by a number of factors recommended by FAO [11]. The optimum dam height and its reservoir storage volume can be estimated by using the Digital Elevation Model programs with the GIS technique (GIS-SRTM), which consists of integrating GIS with the digital elevation model generated by the Shuttle Radar Topography Mission (SRTM) data [12, 13].

The main objective of this study is to develop a new methodology for selecting sites of small dams series by using GIS and finding the optimum height by means of a proposed mathematical model. The computer program is constructed and named the OHALM. It must be noted that this is the first study that focuses on the evaporation parameter to find the optimal water level for small dam reservoirs according to an economic aspects based on the lowest evaporation losses and highest storage capacity. The proposed model was checked by comparing its results with two existing dams in the western desert of Iraq that was constructed before five decades [14].

2 Materials and Methods

2.1 The Study Area

Horan Valley is the largest valley in Iraq, with a catchment area of 13,370 km^2 (Figure 1). It is extending for a distance of 458 km, starting from the Iraqi-Saudi border, until it meets the Euphrates River in Al-Baghdadi city. The geographical location of the valley is between the longitude $39°00'00''$ to $43°00'00''$ East and the latitude $32°00'00''$ to $43°00'00''$ North. The elevation difference between the valley upstream and downstream is around 600m [15]. The Horan Valley region is classified as an arid region with an annual rainfall average of 110 mm; it has a hot summer and a cold winter [16]. The average annually evaporation depth ranges from 1600 mm to 1900 mm, and about 75% of these evaporations occur between April and September [17]. The maximum annual surface runoff rate is about 900 million cubic meters [16]. Most of the catchment area of Horan Valley is composed of hard limestone rocks, and these rocks are a good base for dams [18].

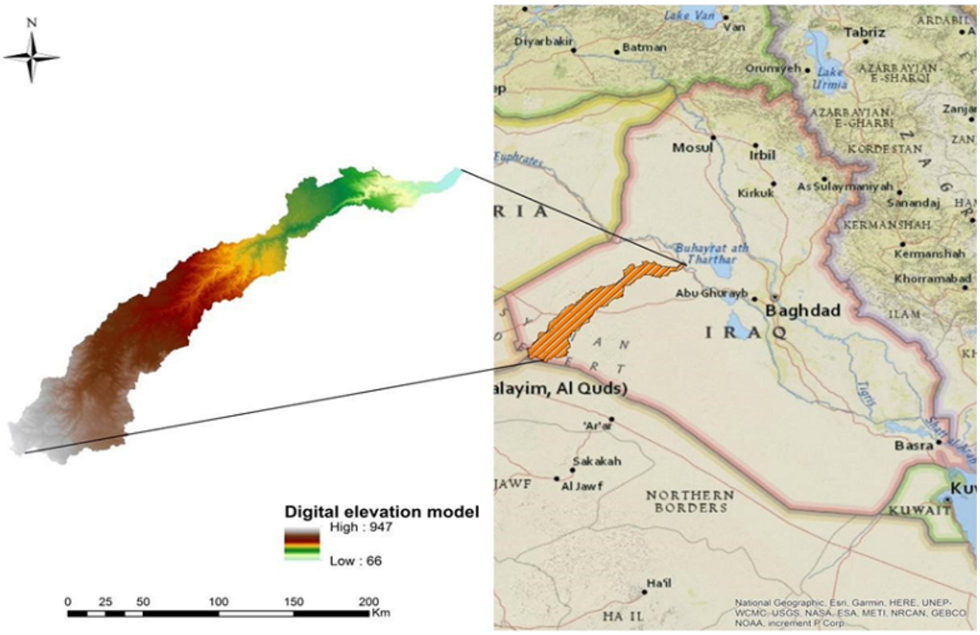

Figure 1. The study area

2.2 General Approaches

The research work consists of two stages, which can be summarized as follows:

1. Dam sites are selected by using GIS through a set of criteria.

2. The optimal height of the dam is designed by formulating a computer program using VB software, this program is named as Optimal Height and Location Model (OHALM).

2.2.1 Dam location selection criteria

Topographic data plays a major role in defining the appropriate location for the construction of dams [19]. Six major factors have been identified by FAO for determining the dam's sites: the climate changes, The hydrology, the topography, the agronomy, the soils, and the socio-economics [11]. According to the available data and the required considerations, two important considerations was taken in this study: the first one is dividing the study area into upstream, midstream, and downstream, while the second is suggesting that the maximum number of dams in any series is five dams.

- Stream order:

As a parameter of hydrology, stream order has been chosen as one of the criteria to find the optimal dam location because of its effects on flood volume, as it is extremely increased in streams that have a higher stream order and vice versa [20]. The arrangement of stream order depends on the connection of tributaries and allows the classification of stream orders according to their size, such as the lower stream orders having a higher area and higher permeability and infiltration, and vice versa [16]. To extract the stream order, four steps were conducted: flow direction, flow accumulation, defining a threshold for drainage flow accumulation, and Strahler classification. Figure 2 explains the stream order map of the study area.

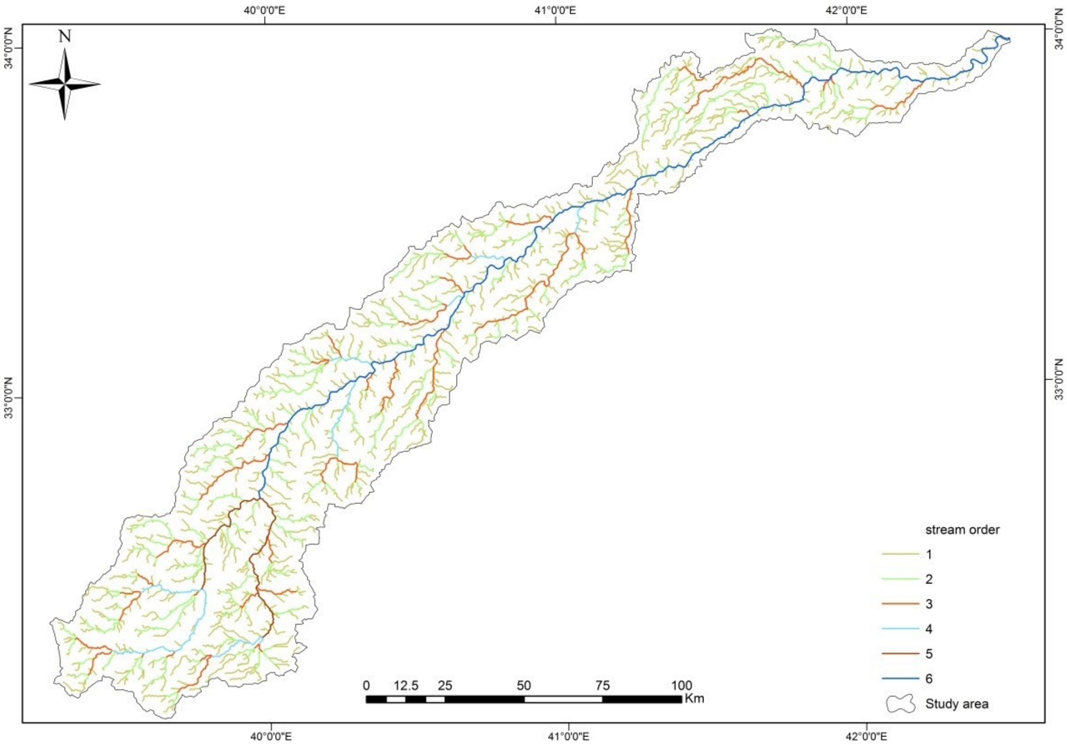

Figure 2. Stream order map

- Valley width:

One of the main features that should be considered when constructing dams is the width of the valley, the height of its banks, and the narrow canyon. The proposed site will reduce the dam dimensions, so the construction cost will decrease [21]. Figure 3 shows the cross-section of the suggested dam site, while Figure 4 explains the contour lines for the suggested dam site.

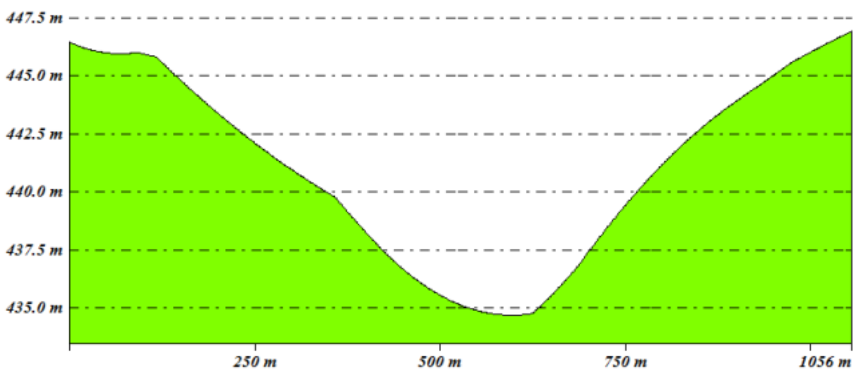

Figure 3. Cross-section for suggested site

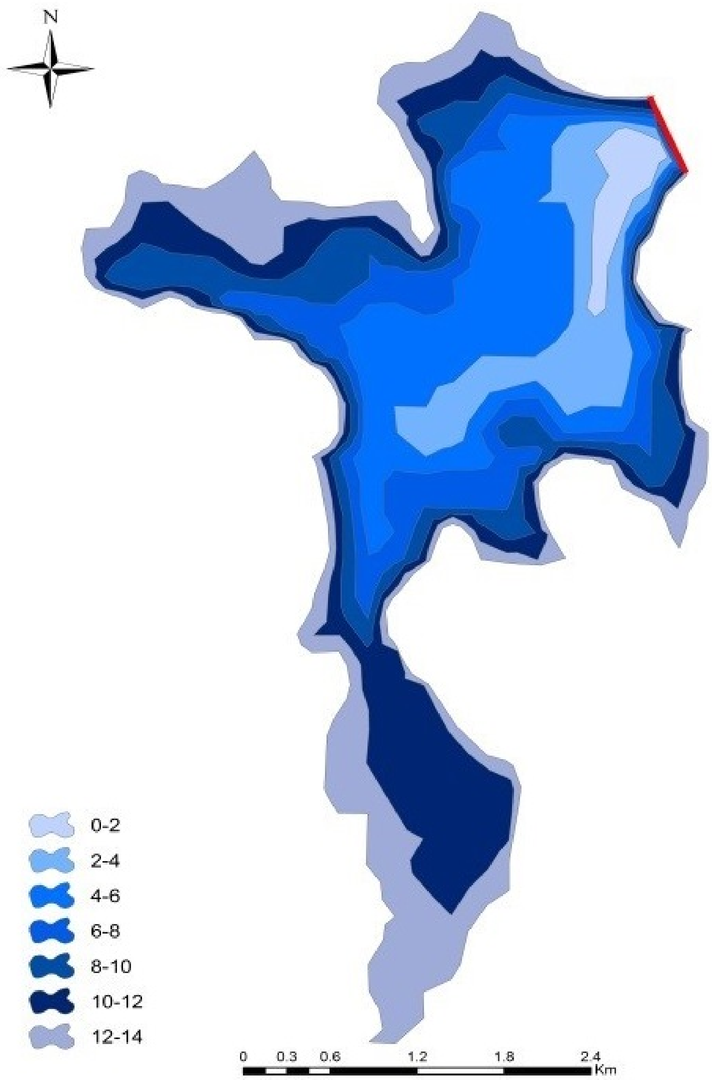

Figure 4. Contour lines for suggested site

- Valley slope:

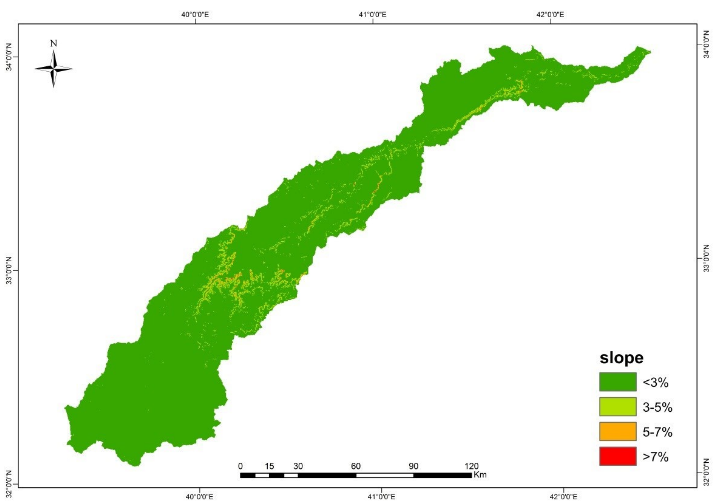

Figure 5. Slope map

As a topographical parameter, the valley slope was chosen as one of the major considerations to finding the optimal small dams' location. It plays a main role in generating surface runoff so it will affect the sedimentation, the speed of water flow and the quantity of material required to build the dam structure [16]. The valley slope map is very important for the runoff analysis in hydrology studies. The reservoir slope must be less than 3% in order to get the best storage efficiency and more economical earthwork [22]. Areas of a slope greater than 5% are not suitable to construct dams because of irregular distribution of runoff that followed with high rates of erosion and large earthwork being required [23]. The slope of the study area is explained in (Figure 5).

- Dams series formula:

One of the characteristics that must be considered when constructing a small dam's series in a specific area is the location of the second dam relative to the first one that selected according to the limitations above. This criterion depends mainly on the height of the first dam, which includes the maximum water level, freeboard, and topography of the valley. The maximum water level represents the optimum water level that was found depending on the established criteria. Freeboard is the difference in height between the total dam height and the maximum water level; its value should be sufficient to prevent floods above the dam, as many dams was failed due to insufficient freeboard [24]. The United States Bureau of Reclamation (USBR) recommends that the freeboard used in the dams will be about 1.5 m to 3 m [25]. As for the topographic conditions, they were set to add protection to the dam and prevent the effects of the backwater curve (Figure 6).

$$B.L_B = Spillway\ level_A + F_b + \lambda \tag{1}$$

where:

$B.L_B$ = Bottom level of the second dam (B), (m)

$Spillway\ level_A$ = Optimum water level of the first dam (A), (m)

F_b = Free board (m)

λ = Coefficient of topographic (m)

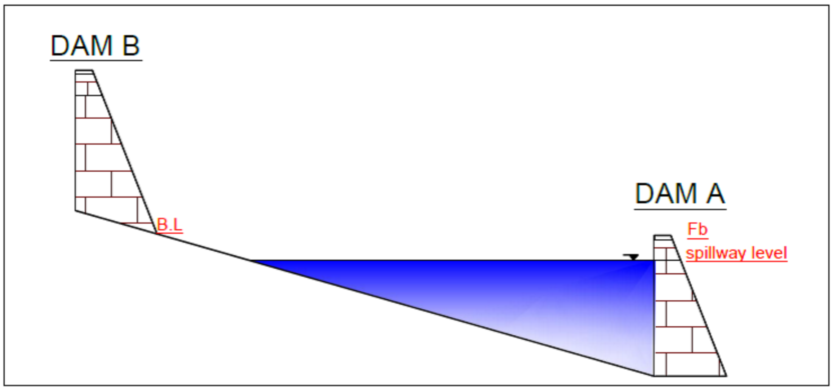

Figure 6. The series formula description

- Distance from main roads:

Roads are considered as a socio-economic parameter and have been chosen as one of the basic criteria for finding dam series locations, the dam's sites should not be far from the existing roads to reduce construction costs [26]. A 250-meter buffer zone has been used around all roads, including unpaved roads [22]. To prevent any future conflict between the constructed dams' sites and roads, a threshold value of less than 5 km was chosen [27]. Figure 7 shows paved and unpaved roads in the study area.

2.2.2 Site identification

The suitable site for a series of small dams was identified by GIS, represented by the Global Mapper 20 software and the ArcMap 10.5 program. Alsu used GDEM extracted from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data and Quick Bird satellite images as input data. The identification process is done through the visual interpretation of the satellite image.

2.2.3 Model description

The mathematical model of the optimum water level for suggested dams can be formulated as follows: Select {D} = dam location.

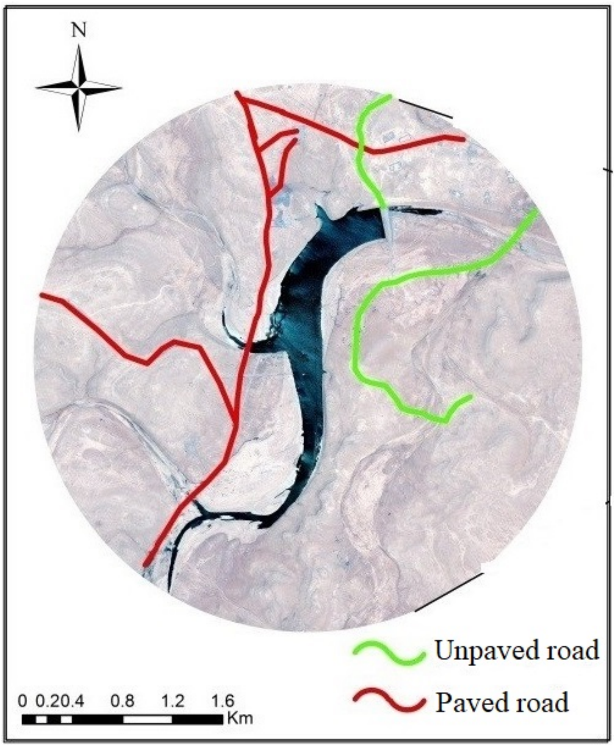

Figure 7. Paved and unpaved roads near one of the existing dam

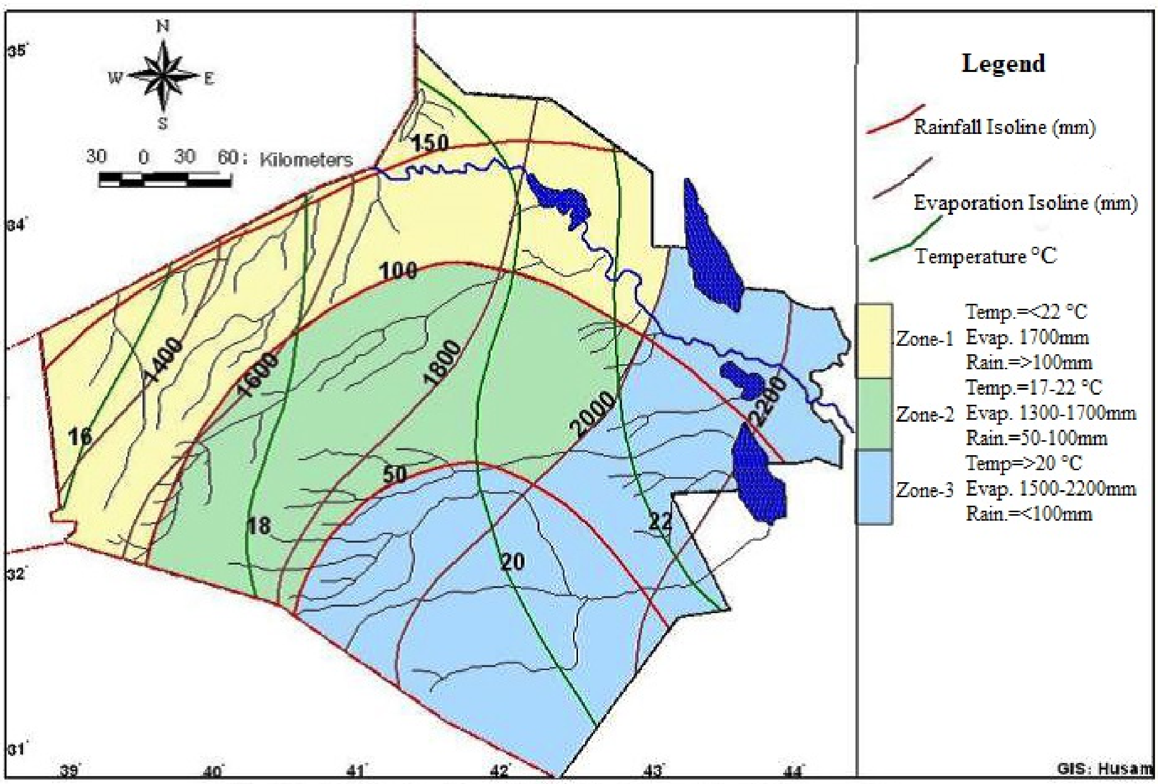

Figure 8. The distribution of rainfall, evaporation and temperature [28]

To maximize the objective function (F), which can be written as:

$$F = \frac{\Delta VS}{\Delta VE} = \frac{\left(V_{(i+1)} - V_i\right)}{\left(S \cdot A_{(i+1)} * d_E - S \cdot A_i * d_E\right)} \tag{2}$$

F = objective Function of the benefits
$S.A_i$, $S.A_{(i+1)}$ = reservoirs surface area at water level i & $(i+1)$ respectively (m^2)
d_E = Evaporation depth (m)
V_i, $V_{(i+1)}$ = reservoirs storage volume at water level i & $(i+1)$ respectively (m^3)
i = rank of water level
The following constrain could be used:
$H_{max} \geq W.L \geq H_{min}$
H_{max}, H_{min} = the maximum and minimum reservoir water level respectively (m).
$W.L$ = the optimal water level in the reservoir.

ASTER data was used in the creation of contour maps through the GIS represented by the Global Mapper 20 software and the ArcView 10.5 program, with the analysis and processing of spatial and descriptive data that are of great importance in the design of dams, where the volume and surface area of the reservoir were calculated. The evaporation losses from the reservoir water surface it is estimated according to the field data that explained in the map (Figure 8), which shows the distribution of rainfall, evaporation, and temperature in the Iraqi western desert, the evaporation depth was estimated for the selected locations by interpolation according to this map.

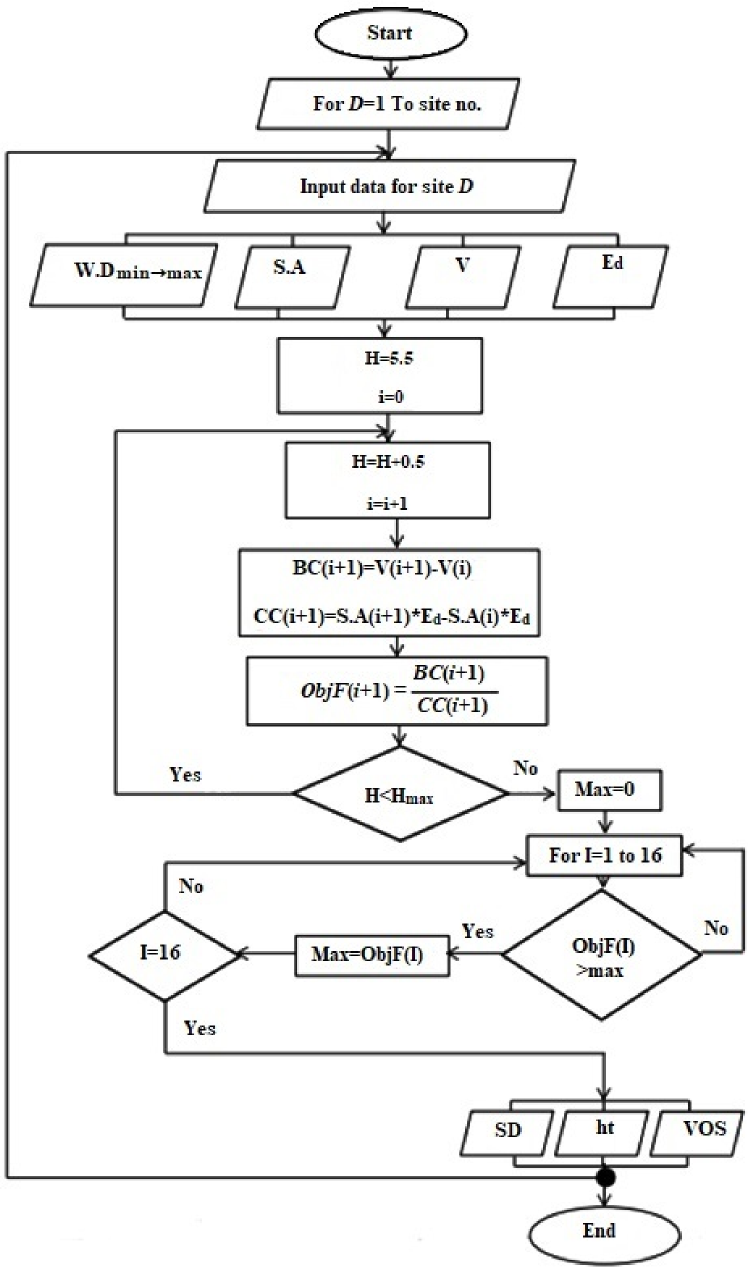

Figure 9. OHALM logic flow chart

2.2.4 Visual basic model

The proposed model (OHALM) aims to estimate the optimal water level by minimizing evaporation losses from the reservoir surface area and maximum storage capacity for the given small dams' series. There are some principle assumptions were considered to formulate this model [29]. This model can be summarized in the general steps illustrated in Figure 9.

3 Results and Discussion

3.1 Division of Study Area

Horan Valley is the largest valley in the Iraqi western desert, so the valley area is divided into three regions, as shown in Table 1.

Table 1. Zones of Horan Valley

Part	Part Name	Total Area km^2	Area Around Main Stream km^2	Length of Main Stream km
1	Upstream	7078.15	3114.47	73.7
2	Midstream	3250.88	3250.88	108.5
3	Downstream	2810.85	2810.85	167.32

3.2 Proposed Site Identification

The most important factors affecting the selection of the small dam site can be summarized as follows:

1- The dam must be located on the main stream of the valley.

2- The cross-section width of the selected sites ranges between 450 and 1750 m to reduce the dimensions of the dam, thereby reducing construction costs.

3- The slope of the dam reservoir is less than 3% to provide high storage efficiency and economical earthwork.

4- The distance between the proposed dams and the existing paved or unpaved roads, is between 250 and 5000 m.

5- After the first dam location is selected, the optimum storage water level is estimated using the OHALM, then Eq. (1) is applied to determine the location of the second dam, and so on for the remainder (Figure 10).

6- The proposal dam location was chosen by using the Global Digital Elevation Model (GDEM) and GIS techniques.

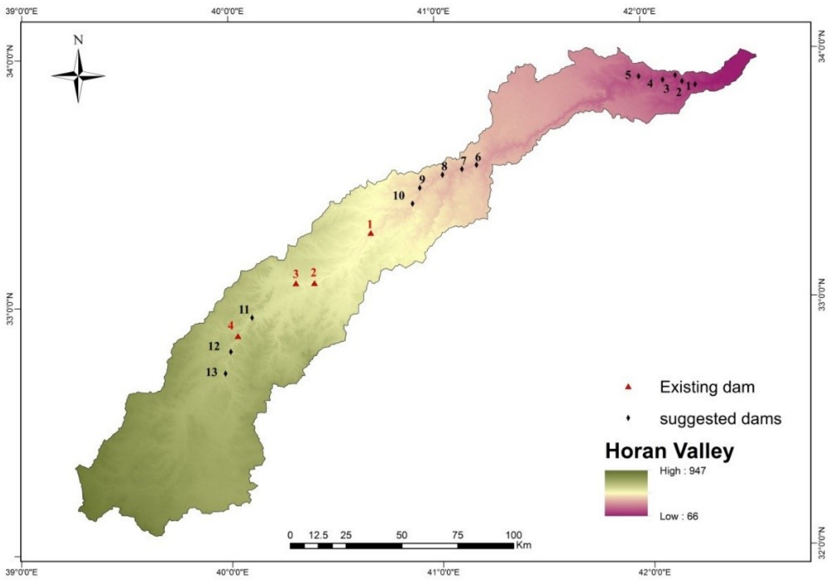

Figure 10. The proposed dams sites

3.3 Input Data for Model

After finding the proposed site for the first dam and through the contour map, the reservoir surface area and the storage volume of storage are calculated. These values are entered into the visual basic program. The minimum storage depth Hmin is assumed to be equal to 6 m, depending on the information about the existing small dams, such as Horan 2 dam, and represents the dead storage for the reservoir, which is greater than the evaporation losses of three drought years. There is no significant difference between the objective function values for most of the suggested dams. Therefore, we chose H = 14 m as the maximum water depth for the suggested dams, as shown in Figure 11. This height very close to the average height of the existing small dams in the Western Desert (about 14m). The model iteration started from the minimum value then increasing by 0.5 m in each iteration. As for the depth of evaporation, its value was found for each region based on the field data (Figure 8), where the depth of evaporation losses in Horan Valley can be classified according to field data into three regions: upstream, midstream, and downstream. The annual evaporation depths in these regions were 1600 mm, 1700 mm, and 1900 mm, respectively. The data is entered into the program, depending on the mathematical model that was illustrated in the flowchart (Figure 9). Figure 12 explains the OHALM model run interface for all suggested sites.

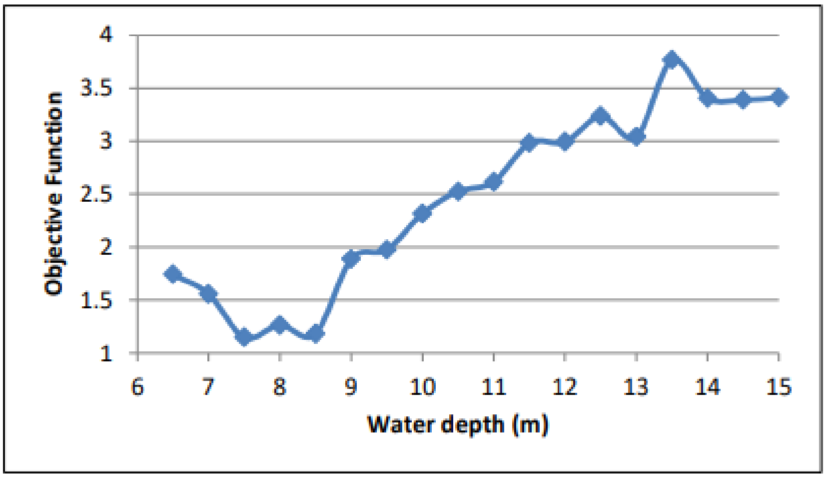

Figure 11. Objective function versus water depth for suggested dam

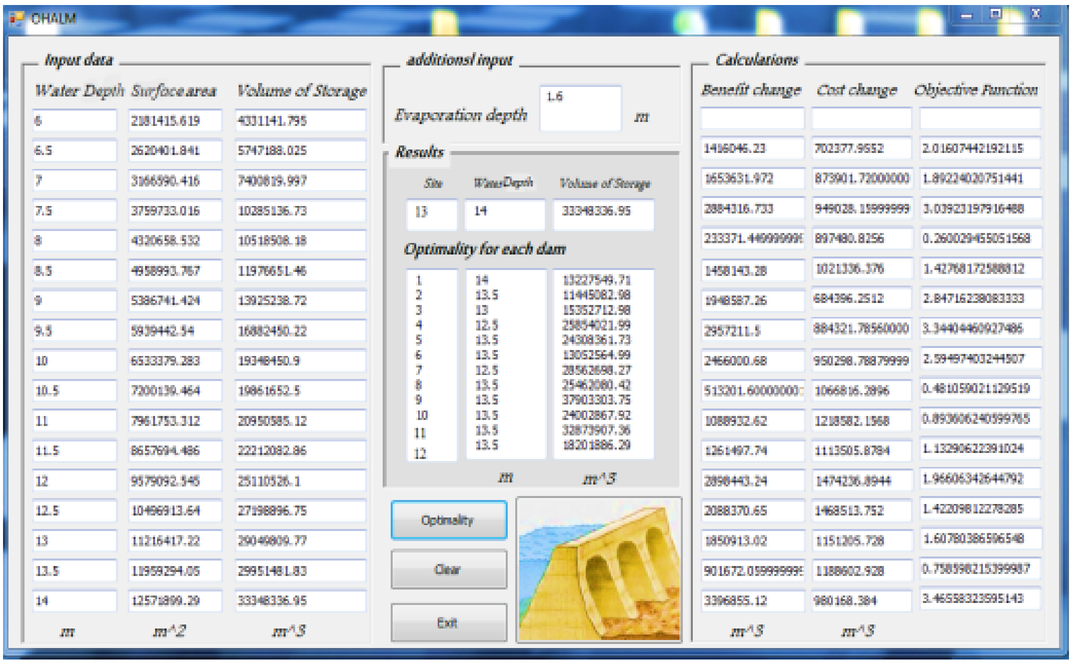

Figure 12. OHALM model run interface for all suggested sites

After running the program (OHALM) and finding the optimum water level for the first site, a free board is added (2.5 m) and the value of the topographic coefficient that was used in this study (0.5–1) m to find the location of the second dam, these criteria will be applies to all selected sites.

4 Conclusions

The study's findings demonstrated the applicability of this strategy in identifying a sequence of diminutive reservoirs with small dams height about 12.5 m to 14 m. These heights will be compared with the existing dams heights that constructed in the last five decades (AlRutba dam, Horan 2, Horan 3, Al-Ga'ra 4, and Al-Ga'ra 2) in Horan Valley and the surrounding areas. The study's finds that the differences between the dam height derived from the mathematical model and that of existing dams are around 10.4%, 7.2%, and 7.2% for the upstream, midstream, and downstream areas, respectively. The discrepancy in water levels between the AVE curve and the current dam is approximately 13.8%, 18.4%, and 9.27% upstream, midstream, and downstream, respectively. The mean depth of the current dams is 12.4 m. In OHALM, the depths were 13.7 m, 13.3 m, and 13.3 m in the upstream, midstream, and downstream respectively. In AVE-C, the depths were 10.69 m, 10.12 m, and 11.24 m in the upstream, midstream, and downstream respectively. In terms of storage capacity, the OHALM approach is capable of saving twice the amount of water quantity compared to the average storage capacity of existing dams. Additionally, it outperforms the AVE-C method for the same proposed dams. The average storage capacity of existing dams is 10.67. The estimated storage capacities for OHALM in the upstream, midstream, and downstream areas are 18, 25.78, and 28.1, respectively. For AVE-C, the anticipated storage capacities in the upstream, midstream, and downstream areas are 11.9, 15.68, and 18.36, respectively.

This suggests that the methodology can be utilized to determine the optimal dam height in arid regions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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